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Ratooning as an adaptive management tool for climatic change in rice systems along a north-south transect in the southern Mississippi valley

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ABSTRACT

The effect of climate change on recent and projected increases in surface temperatures is well-documented. For agriculture, such changes can impact crop phenology and production, but the degree of impact will depend, in part, on contemporaneous changes in crop management. In the current study, we quantified recent (last 40 years) and projected (to 2095) changes in air temperature and associated changes in growing season duration for rice along a latitudinal north-south gradient of the lower Mississippi valley. Recent and projected climate data indicated an ongoing increase in air temperature and growing season length with latitudes above ~31 °N. We then applied the DD50 growing degree day model to these data to determine if ratooning, a management practice that produces a second rice harvest with minimal resource input, could be employed. The model results were analyzed and used relative to the southernmost location, Cameron Parish, where the season length and daily temperatures currently allow for ratooning to be a common practice for long-grain cultivars (e.g., Cocodrie, Catahoula). The recent and projected increases in temperature and seasonality indicate that ratooning could already be adopted in Avoyelles Parish, and is potentially possible as far north as Cape Girardeau County (37 °N) by the end of the 21 st century. While additional information regarding possible effects of heat stress, water availability, rising carbon dioxide (CO_2) levels, and other factors will be necessary to fully assess ratooning potential, our research indicated that ongoing increases in temperature and season length may allow agronomic management practices, such as ratooning, to help adapt rice production to climatic uncertainty.

1. Introduction

To maintain current production levels, it will be necessary to adapt existing production systems to accommodate greater climatic uncertainty (Boote et al., 2011; IPCC, 2014). Research regarding potential adaptation approaches frequently focuses on evaluation of crop genotypes and/or traits that confer tolerance to drought or heat stress, improved yield quality or nutritional content (e.g. Ramirez-Villegas et al., 2015; Tao and Zhang, 2010). Such studies include and evaluate a broader range of genetic traits designed to maximize genetic by environment interactions (i.e. GxE) (Ziska and McClung, 2008; Godfray et al., 2010; Wang et al., 2016).

Rice (*Oryza* sativa) cropping systems are of global importance in terms of food security (Sandhu and Kumar, 2017). With respect to climatic uncertainty, changes in mean, night-time or the frequency of extreme temperatures pose a serious risk for rice production, particularly during anthesis (e.g., Peng et al., 2004), and such impacts are likely to occur in major rice growing regions, including the U.S. (Parry et al., 2004). Because of these risks, adaptive research in rice has been directed towards understanding temperature induced yield limits and the counter-means by which rice systems may improve resilience, both quantitatively and qualitatively (Ziska and Manalo, 1996; Matsui et al., 2001; Prasad et al., 2006).

Yet, in addition to a GxE approach, assessing environment by management (i.e. ExM) practices can also play a significant role in adapting major cropping systems in the U.S. For example, Lobell et al. (2002) indicated that adaptive agronomic management at the farm level, (the ExM component), can have a major impact on maintaining regional wheat production in response to climate variability. Similarly, for rice systems, water savings methods such as alternate-wetting drying (AWD) are being evaluated to determine cost-benefit savings and yield impacts (Massey et al., 2014). Espe et al. (2016) has suggested that rice farmers may already be adapting to a warming climate by planting earlier to take advantage of earlier Spring temperatures and longer growing seasons. Thus, simple management strategies may be effective in responding to changing temperature conditions, either

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without, or in concert with, GxE adaptation approaches.

The ability of ratooning as an adaptive ExM tool in the context of climate uncertainty has not, however, been evaluated. Ratooning is a management option in rice systems that allows for rice regrowth leading to a second or ratoon crop (RC) harvest following that of the main crop (MC). The ratoon crop yield can be as high as 50% of that produced from the main crop, with lower production costs due to savings in land preparation, labor and water use (Harrell et al., 2009).

Because temperatures and growing season duration are limited in the northern rice growing areas, at present, in the United States, ratooning is only implemented in the most southern region of the Mississippi valley. However, the practice may be an effective ExM adaptation approach as projected changes in climate could result in a warmer and extended growing season (Negalur et al., 2017). In this context, ratooning management could serve as an approach for U.S. rice growers to benefit from a warmer climate by increasing annual grain production with only a minimal increase in input and operational costs.

In this study, we evaluate ratooning as an adaptative ExM strategy for rice systems in the U.S. Mississippi Delta. Recent (since 1976) climate trends in this region are quantified to identify temporal changes in air temperature as well as shifts in growing season duration in a latitudinal south-north transect for five locations. The well-established DD50 model, a growing degree day based approach used by rice growers to predict rice development (Norman et al., 1998; Frizzell et al., 2007), is then utilized to evaluate changes in thermal time requirements for rice MC and RC for recent and projected climates. The southernmost transect location, Cameron Parish, Louisiana where a range of rice cultivars are grown (e.g., CL 111, Cocodrie, Catahoula, inter alia) and where ratooning is a common practice was used as a meteorological guide. Our objective was to determine if, or when, each location north of Cameron Parish would achieve the minimum thermal time requirement and season length necessary for ratooning to be implemented.

2. Materials and methods

2.1. Recent temperature changes

A web-based software program, iAIMS Climatic Data developed by Texas A&M University (Yang et al., 2010) was used to obtain daily maximum and minimum air temperatures for five rice growing locations along a south-north transect from 1976 through 2016. The weather data in this program is measured / observed daily climate data as obtained from the National Climatic Data Center of the National Oceanographic and Atmospheric Administration and other weather stations as detailed in Wilson et al. (2007). The year 1976 was chosen as the earliest date as it represents the onset of recent increases in the global land-ocean temperature index (Dieng et al., 2017). The five stations chosen are representative of the latitudinal gradient in the lower Mississippi valley where the bulk of U.S. rice is grown (Fig. 1).

Temperature data obtained from each of the five locations was used to initially calculate changes in frost free days (from last Spring to first Fall frost), where frost was defined to have occurred when minimum daily air temperature was below or equal to 32 °F. These data were then analyzed using the modified growing degree day, DD50, rice model. This model is based as follows:

$$DD50 = \Sigma\ [(T_{max} - T_{min}) / 2] - 50$$

Where DD50 is computed daily using Tmax and Tmin air temperatures. Tmax is restricted to a maximum of 94 °F (34.4 °C), Tmin to a maximum of 70 °F (21.1 °C) and minimum of 32 °F (0 °C), so that daily DD50 units are constrained from a range of 0–32 degree-days.

The DD50 data was then analyzed from 1976 to 2016 for each of the five locations to determine potential changes in seasonality in the context of rice production. The first analysis was to quantify yearly cumulative DD50 values to assess if there was a significant temporal change in air temperature during the frost-free period for that location. IN this context, DD50 values were a general metric for assessing temporal changes in relevant thermal units during the growing seasons, and thus not assessed to specific rice cultivars. The second analysis was to determine the cumulative DD50 requirement for ratooning using August 15th as a starting date (average of when the MC harvest historically occurs). We also explored effects of changing climate on varying planting dates, predicted maturity dates, and thus ratoon dates, based on DD50 unit requirements averaged across several conventional and hybrid lines grown in the Mississippi Delta region (Frizzell et al., 2007) as described later in this section. The southernmost location, Cameron Parish, Louisiana, where ratooning is a common management practice, was used to define the reference temperature and seasonal parameters associated with ratooning. We used a proximate value of 90% of the average 1976–2016 cumulative DD50 for the ratooning period from Cameron Parish as a guide to indicate a thermal time threshold for ratooning practice in the other four locations. Lastly, the number of frost-free days for ratooning (i.e. from August 15th to the first fall frost) was determined for all locations and compared to a 75-day minimal ratooning requirement (LSU Extension, Dustin Harrell personal communication).

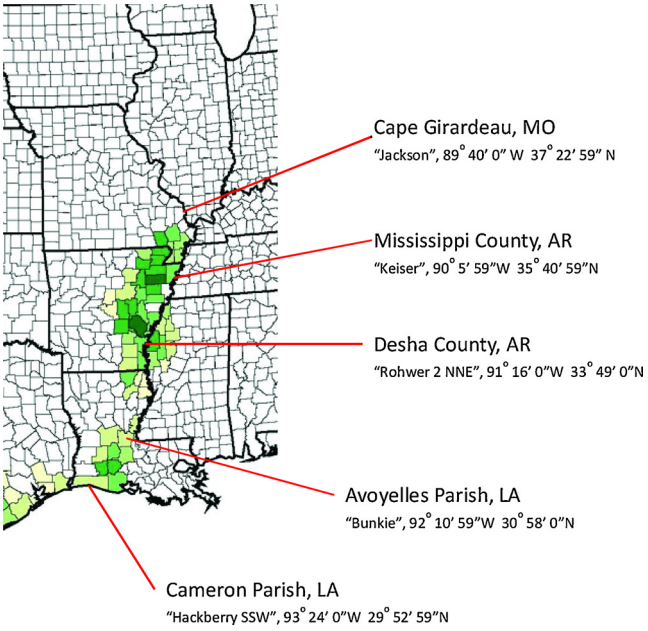
Cape Girardeau, MO
"Jackson", 89° 40′ 0″ W 37° 22′ 59″ N
Mississippi County, AR
"Keiser", 90° 5′ 59″W 35° 40′ 59″N
Desha County, AR
"Rohwer 2 NNE", 91° 16′ 0″W 33° 49′ 0″N
Avoyelles Parish, LA
"Bunkie", 92° 10′ 59″W 30° 58′ 0″N
Cameron Parish, LA
"Hackberry SSW", 93° 24′ 0″W 29° 52′ 59″N

Fig. 1. Geographic description of weather stations by county/parish. Original map was extracted from USDA NASS (2010). Weather stations are from https://beaumont.tamu.edu/CLIMATICDATA/WorldMap.aspx.

2.2. Projected temperature changes

We used an average of six spatially downscaled and bias corrected general circulation models (GCMs) to estimate daily maximum/minimum air temperatures for a given location for selected years (2030, 2050, 2070, and 2095) for Representative Concentration Pathways (RCPs) 4.5 and 8.5 (Table 1) from the IPCC 5th approximation (IPCC, 2014) as per the MarkSimGCM weather generator (www.gisweb.ciat.cgiar.org/marksimgcm). The results of thirty independent runs at each of the selected years were conducted to estimate annual daily weather variability at each of the selected years. The MarkSim weather generator incorporates methodology to address differences between observed and simulated weather variables for each GCM using a 50-year hind-cast at a spatial resolution of 1 to 2°. A 5th order polynomial is used to model this difference which serves as a method to bias correct each GCM and account for hind-cast differences. A 3rd order polynomial

Table 1
General circulation models (GCMs) used for the RCP4.5 and RCP8.5 analysis with MarkSimGCM weather generator.

GCM Name	Reference
CSIRO-MK3.6.0	Collier et al. (2011)
GFDL-CM3	Donner et al. (2011)
GFDL-esm2g	Dunne et al. (2012)
HadGem2-ES	Collins et al. (2011)
IPSL-CM5A-LR	Dufresne et al. (2013)
MIROC5	Watanabe et al. (2010)

is subsequently used to spatially interpolate the raw GCM data to a finer scale resolution of about 1 km (Jones and Thornton, 2013). MarkSimGCM links the MarkSim standalone program (Jones et al., 2002; Jones and Thornton, 2003) with 30 arc-second climate surface data derived from the WorldClim database (Hijmans et al., 2005). Results were bias corrected using local weather stations and spatially downscaled as per Jones and Thornton (2013).

Custom written scripts using Python (v2.7) were developed to parse climate data and calculate growing season duration and thermal time data daily. For future climate analyses, averages and standard deviations were pooled across the 30 runs at each year of interest. In addition to evaluating ratooning requirements with the assumption of a fixed August 15th harvest date for the MC, we also explored potential changes in earlier planting date, and hence MC maturity dates and RC start dates, resulting from future warming temperatures. This so-called variable planting date analysis utilized several assumptions. First, planting occurred when at least five consecutive days with minimum 10 °C (50 °F) air temperature were available (Moldenhauer et al., 2013), and seven days were required after planting for seedling germination (Wilson et al., 2013). To estimate MC maturity, a conservative value of 2211 DD50 units were required from emergence through 50% heading for a typical long-grain cultivar grown in the Southeast U.S. These requirements were derived from analysis of the work of the work of Frizzell et al. (2007) where conventional (Bowman, Cybonnet, Francis, Jupiter, Pirogue, Presidio, Spring, Trenasse, and Wells) and hybrid (CL 161, CL 171 AR, CL XL729, CL XL730, CL XP745, CL XL723, CL XP 744) variety DD50 requirements were averaged to represent thermal requirements of a single cultivar. Assuming a standard 35 chronological day post 50% heading stage requirement to maturity date (Wilson et al., 2003), we obtained an average additional DD50 requirement of 1094, 1100, 1075, 1047, and 1011 units for Cameron, Avoyelles, Desha, Mississippi, and Cape Girardeau Counties via back-calculating cumulative DD50 units from the historical data (1976 through 2016) with an August 15th MC maturity date. These thermal time requirements and estimated planting dates were subsequently used to predict future MC and RC dates for the RCP 8.5 and 4.5 scenarios.

We conducted an additional hindcast comparing predicted seasonal cumulative DD50 units from 2010 through 2017 for each GCM as compared with historical climate results (Table 2). Note that 2010 was the earliest prediction year available in MarkSim due to limitations with the WorldClim database. When averaged across all GCMs and years, predicted cumulative DD50 results were less than +/- 16 units as compared to historically-derived values for all locations, and Cameron, Avoyelles, and Desha counties showed even smaller differentials less than 5 units in magnitude. Except for Avoyelles county, thermal units were slightly under-predicted with the GCMs than the observed results. These results indicated that the GCMs output implemented in the MarkSim protocols can be used to provide reasonable forecast into the future for the five selected locations.

Statistics. Regression of three seasonal metrics (Last Frost, First Frost and Frost Free Days) were determined form 1976–2016 for all locations and used in the DD50 analysis seasonally and for ratooning characteristics relative to the Cameron Parish location. P values were determined to ascertain whether there was a significant correlation with recent temperature changes. Regression analysis was done using Statview Software (Cary, NC, USA).

Table 2
Results of partial hindcast comparing cumulative DD50 units from May 1st through Sept 1st averaged from 2010 through 2017 as predicted by six GCM simulations from the MarkSim weather generator*. Historical results are indicated as are the average result across all GCMs for a given location.

	Cameron	Avoyelles	Desha	Mississippi	Cape Gerardieau
Average CDD50 per GCM					
Csiro	3662	3614	3501	3401	3175
gfdl-cm3	3700	3643	3518	3415	3187
gfdl-esm2	3684	3662	3542	3435	3170
Hadgem	3696	3665	3575	3468	3238
Ipsl	3701	3654	3547	3437	3180
mirco5	3713	3694	3593	3465	3244
Averaged CDD50 Across all GCMS					
GCM average	3692	3655	3546	3437	3199
Averaged Observed CDD50					
Observed average	3696	3651	3448	3448	3215

* MarkSim methodology requires the use of an RCP scenario for hindcasting. RCP 2.6 was selected as the most relevant with respect to this short hindcast period.

3. Results

3.1. Recent

Assessments of the transect since 1976 indicated significant changes in the last spring and first fall frost for the two northerly locations (Mississippi and Cape Girardeau counties), and a significant increase in frost free days with year for all locations north of Avoyelles Parish (Table 3). Although not significant, similar trends were observed with year for the southern locations as well. Analysis of these data using the DD50 model also indicated significant increases in seasonal, cumulative thermal time units for all measured locations north of Cameron Parish (i.e., Desha, Mississippi and Cape Girardeau counties) (Fig. 2). This was consistent with the increase in growing season length (frost free days) (Table 3) for these locations.

Table 3
Regression of three parameters used in estimating crop season length including (1) Last (spring) Frost (day of year); (2) First (fall) Frost (day of year); and (3) Frost Free Days (FFD) (days per year) over time (1976–2016) for five locations (South to North, see Table 1) along the Mississippi delta where rice is grown. Frost was defined as a day when the minimal temperature was 0 °C or below. Data were taken from (beaumont.tamu.edu/CLIMATICDATA/WorldMap.aspx) for North America. The P value is a measure of whether there was a significant regression correlation from 1976 to 2016 for the parameter. Significant P values are in bold. Values shown are those predicted based on the regression.

Location	Year	Last Frost	First Frost	FFD
Cameron Parish	1976	32	350	320
	2016	29	355	325
	P value	0.773	0.571	0.596
Avoyelles Parish	1976	56	327	269
	2016	52	333	281
	P value	0.628	0.402	0.356
Desha County	1976	78	301	222
	2016	68	320	252
	P value	0.192	0.065	**0.017**
Mississippi County	1976	92	299	207
	2016	76	313	237
	P value	**0.009**	0.077	**0.003**
Cape Girardeau County	1976	110	110	168
	2016	85	309	223
	P value	**0.001**	**0.001**	**0.001**

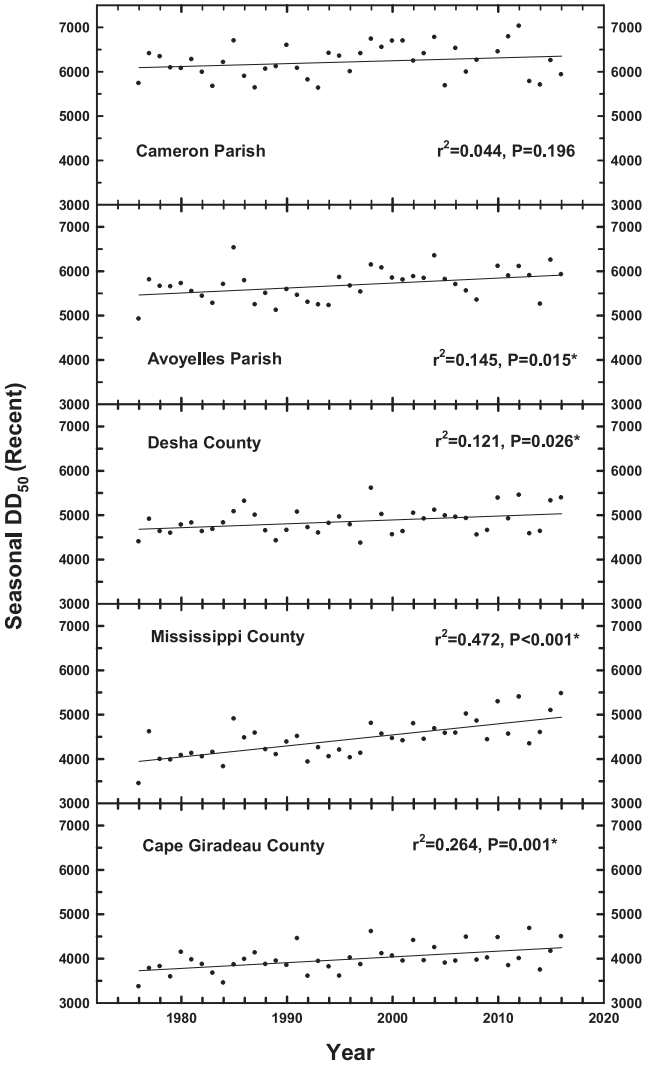

Fig. 2. Recent (1976–2016) changes in seasonal DD50 for the five locations listed in Fig. 1. Significant increases in seasonal trends are noted (*) if $P < 0.05$.

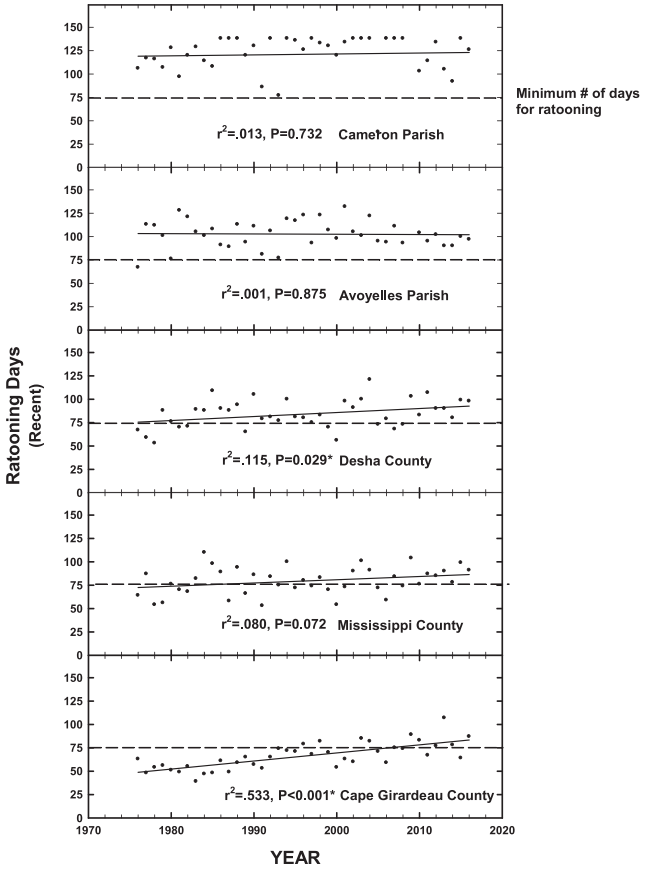

Fig. 3. Recent (1976–2016) changes in the number of days from August 15th to the first recorded frost (i.e. time for ratooning) for the five locations listed in Fig. 1. 75 days (dashed line) is considered the minimum time for ratooning to be implemented. Significant increases in seasonal trends are noted (*) if $P < 0.05$.

Analysis of ratooning days (requiring an assumed minimum of 75 days after MC) from August 15th to first frost indicate that these conditions were routinely observed in Cameron and Avoyelles Parishes, but are now present in Desha, Mississippi, and Cape Girardeau Counties (Fig. 3). However, sufficient increases in cumulative DD50 degree days are also necessary for ratooning. Using a threshold value of 2090 (or 90% of the average cumulative ratooning DD50 for Cameron Parish, where ratooning is commonly practiced), these conditions were only observed after 2011 for Avoyelles Parish (Fig. 4), although significant increases in the ratooning DD50 were noted from 1976 to 2016 for the other three locations (Desha, Mississippi and Cape Girardeau Counties). This suggests that future temperature and season length trends could make ratooning possible at these northern sites.

3.2. Projected

Different radiative forcing values (moderate and high) associated with anthropogenic warming, specifically RCPs 4.5 and 8.5, were used to forecast season length and growing degree values from 2030 through 2095 for these same five locations using the DD50 approach. This forecast also incorporated potential changes in earlier planting dates (Table 2) which, in turn, altered MC and RC harvesting times as indicated in Table 3. Projected data for seasonal DD50 indicated significant linear increases in growing degree days for all locations with the greater relative increase occurring for RCP 8.5 (Fig. 5). However, the relative increase was greater as a function of latitude (e.g. for the RCP 4.5 and 8.5 the percent increase from 2030 through 2095 was 8.6 and 21% and 15 and 36% for Cameron Parish and Cape Girardeau County, respectively) (Table 4 Fig. 5).

For ratooning, earlier planting and increased DD50 values had a significant effect on RC potential. For all locations, RC dates occurred earlier in the season with increasing years. By 2030, apart from Cape Girardeau, MC maturity occurred prior to August 15 (DOY 227) for either RCP (Table 5) for all counties/parishes. By 2070, Cape Girardeau also established an earlier MC date and thus earlier RC date. As consistent with these values the minimum 75-day frost-free ratooning threshold was exceeded in all locations for RCP 4.5 and 8.5 by 2030 except Cape Girardeau county (Fig. 6). However, by 2095, this threshold had also been met (Fig. 6). Similarly, the cumulative degree threshold needed for ratooning (~2090), increased for all projections at all locations (Fig. 7), with the average at or above this value for Cameron and Avoyelles Parishes, and Desha County by 2030. The threshold was exceeded for the RCP 4.5 and 8.5 for Mississippi County and for Cape Girardeau County (RCP 8.5 only) by 2095.

The basis for these predicted changes were the averaged GCM estimates for future temperatures. These were summarized for average maximum and minimum temperatures for RCP4.5, and RCP8.5 scenarios as well as the historical record (Table 6). Historical values from 1976 and 2016 suggest modest increases in temperatures of 1 to 2 °C have occurred during the frost-free period, although it is noteworthy that the length of this period has increased substantially (Table 3),

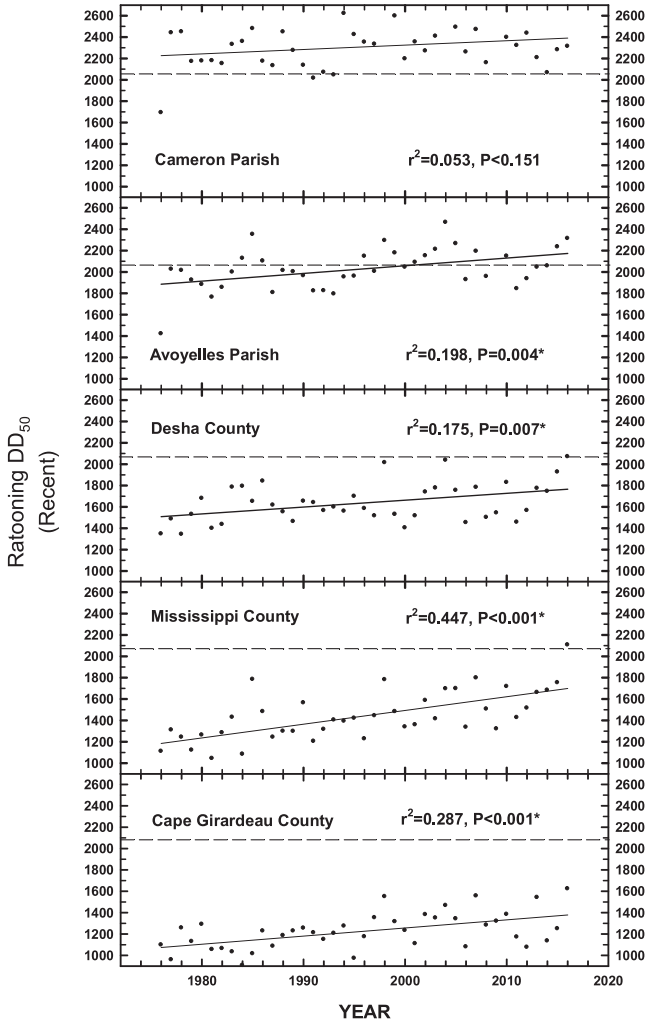

Fig. 4. Recent changes in cumulative degree days using the DD50 model for the five locations listed in Fig. 1 from August 15th to first frost. A 2090 unit threshold (dashed line) was determined as 90% of the Cameron Parish average (1976–2016) and used as the minimum DD50 value necessary for ratooning to occur. Significant increases in seasonal trends are noted if $P < 0.05$.

particularly for the more northern counties of Mississippi and Cape Girardeau. Analysis of future forecasted temperatures indicate similar trends, particularly for minimum temperatures. This suggests that growing season duration, rather than absolute changes in average air temperature, may play a more important role in RC opportunities. Significant changes appear to have already occurred, however, with respect to the number of days during the frost-free period in which either maximum or minimum temperatures exceeded certain thresholds. For example, all locations (except Cameron Parish), the number of days' minimum daily temperatures exceeded 24 °C (75 °F) linearly increased at a rate of roughly 0.5 days per year since 1976 (Table 6), and future trends show even higher rates.

4. Discussion

Recent and projected changes in climate, including warmer temperatures, are expected to have negative effects on global yield of major cereal crops, including rice (Lobell and Field, 2007; Porter et al., 2014, inter alia). Such effects are likely to occur even with CO_2 fertilization, as concurrent increases in CO_2 and temperature do not necessarily result in increased yield for rice (Wang et al., 2015). Adaptation and inclusion of management practices at the field level could play a pivotal role in abating the negative impacts associated with climatic disruption

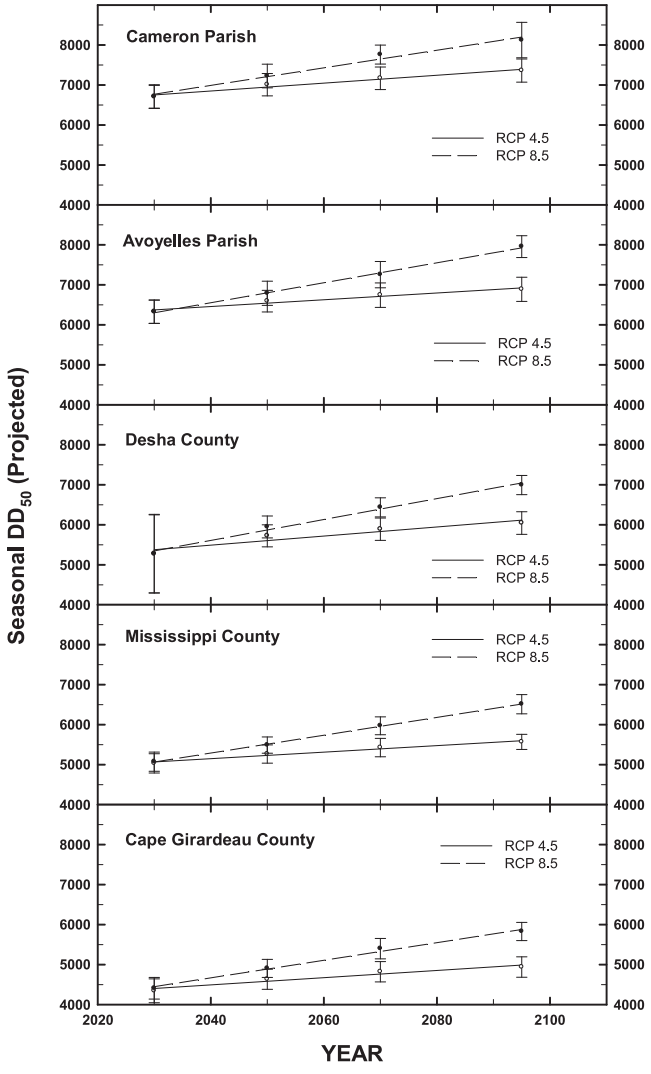

Fig. 5. Same as Fig. 2, but for projected changes in DD50 for RCP 4.5 (solid line) and RCP 8.5 (dashed line) from 2030 to 2095. These projections were based on variable planting date changes as indicated in Table 4. See Methods for additional details. Error bars indicate standard deviations across 30 simulated weather-years for all GCMs at each year.

Table 4
Earliest main crop planting dates (i.e. at least 5 continuous days of Tmin > 10 °C), as a function of the RCP 4.5 and 8.5 models for parish / county along the north-south transect given in Fig. 1. Historical averages (1976–2016) are provided for comparison. Units are in days of year (DOY). Note that June 1st is DOY152. Bars Standard deviations across 1976 through 2016 for historical responses and 30-year predicted weather variations at each decade are shown.

		Cameron	Avoyelles	Desha	Mississippi	Cape Girardeau
RCP 4.5	2030	47±26	56±26	78±24	91±19	108±20
	2050	39±26	52±27	74±26	90±18	103±14
	2070	36±25	50±28	70±27	90±17	102±20
	2095	c29±22	49±28	70±26	88±16	94±19
RCP 8.5	2030	47±26	57±27	81±25	92±18	107±14
	2050	35±24	51±27	72±27	89±16	102±13
	2070	23±18	46±27	65±23	77±21	94±19
	2095	16±12	30±21	55±25	68±23	91±19
Historical		46±26	72±19	92±22	103±16	108±20

(e.g. Lehmann et al., 2013). At present, we are aware of only one previous controlled environment study that has examined ratooning as an adaptive management response to increasing temperatures in rice

Table 5
Earliest MC maturity dates, and RC start dates by extension, as a function of the RCP 4.5 and 8.5 models for the indicated parish / county along the north-south transect given in Fig. 1. Estimates were based on variable planting date results in Table 2 and DD50 emergence through maturity requirements as indicated in the Methods. Estimated dates based on historical climate (1976–2016) were included for reference. Units are in days of year (DOY). Note that August 15th is DOY 227. Standard deviations indicate the 30-year predicted weather variation for each decade.

		Cameron	Avoyelles	Desha	Mississippi	Cape Girardeau
RCP 4.5	2030	200 ± 32	205 ± 23	219 ± 21	226 ± 16	240 ± 21
	2050	194 ± 30	200 ± 20	215 ± 17	222 ± 20	234 ± 17
	2070	191 ± 30	198 ± 21	212 ± 17	220 ± 18	224 ± 45
	2095	187 ± 26	195 ± 19	210 ± 17	218 ± 16	229 ± 15
RCP 8.5	2030	200 ± 32	205 ± 22	220 ± 21	226 ± 17	238 ± 20
	2050	191 ± 27	197 ± 20	211 ± 17	219 ± 17	230 ± 17
	2070	181 ± 8	189 ± 19	203 ± 15	211 ± 16	221 ± 13
	2095	172 ± 12	177 ± 11	194 ± 17	203 ± 14	216 ± 17
Historical		196 ± 50	215 ± 9	231 ± 10	240 ± 12	249 ± 13

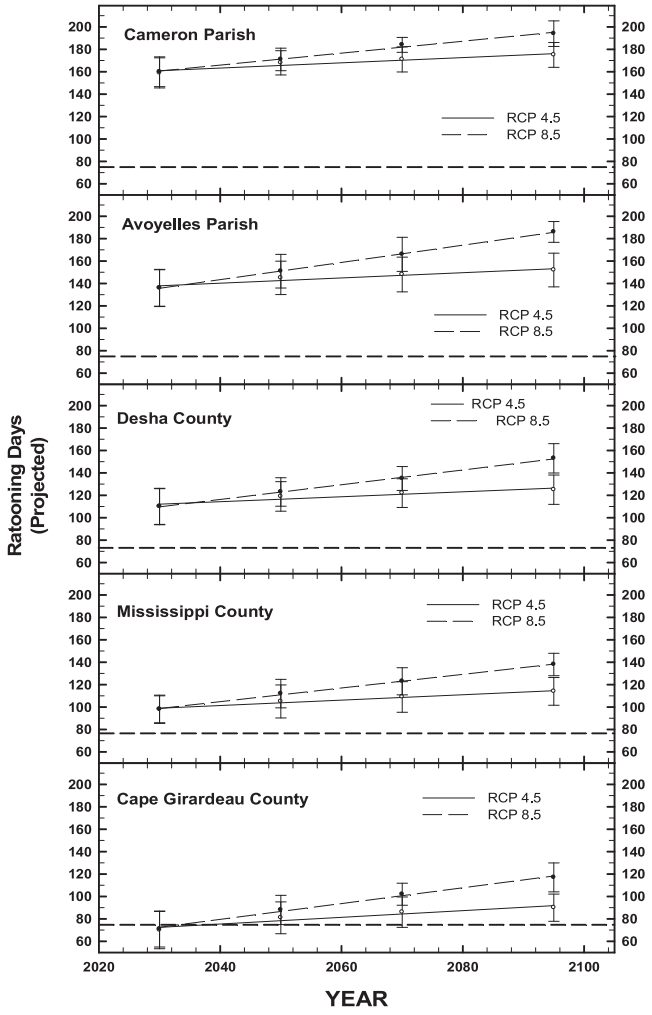

Fig. 6. Same as Fig. 3, but for projected changes in the number of frost-free ratooning days for the RCP 4.5 (solid line) and RCP 8.5 (dashed line) from 2030 to 2095. These projections were based on variable planting dates and hence earlier MC maturity and RC start dates as indicated in Table 3. See Methods for additional details. Error bars indicate standard deviations across 30 simulated weather-years for all GCMs at each year.

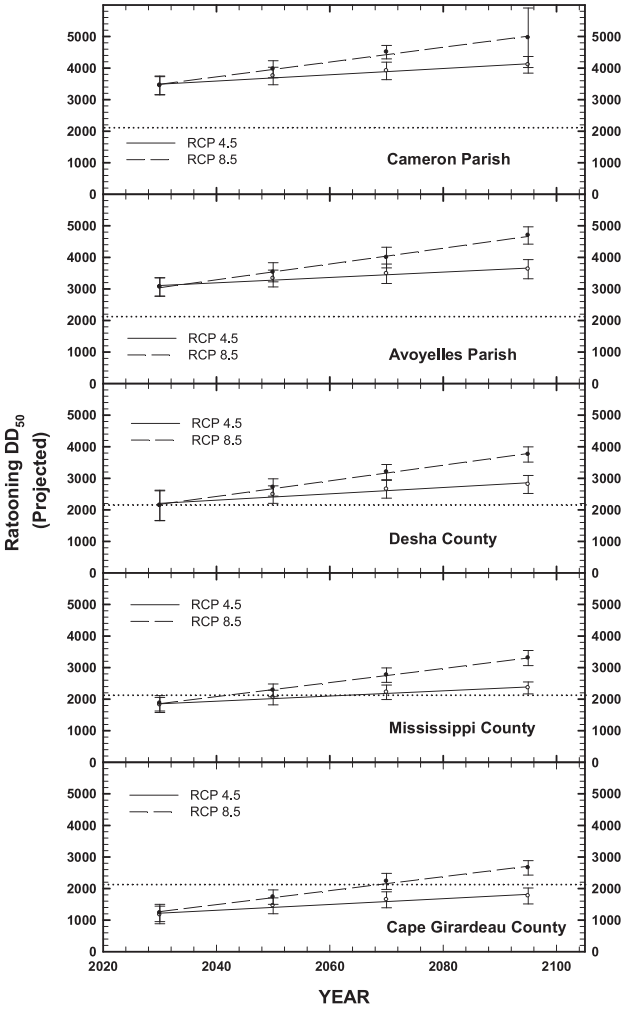

Fig. 7. Same as Fig. 4, but for projected changes in DD50 for the RCP 4.5 (solid line) and RCP 8.5 (dashed line) from 2030 to 2095. These projections were based on variable planting dates and hence earlier MC maturity and RC start dates as indicated in Table 3. See Methods for additional details. Error bars indicate standard deviations across 30 simulated weather-years for all GCMs at each year.

systems (Baker, 2004).

The utility of ratooning will be dependent on temperature and season length. Along the S to N transect evaluated in this study, average minimum daily temperatures have increased as a function of latitude in recent years (1976 through 2016), with significant increases in the duration of the frost-free growing season noted for Desha, Mississippi and Cape Girardeau Counties. Using Cameron Parish (where ratooning is currently practiced) as a guide, the minimum number of days necessary for ratooning (~75, from August 15th to first frost) are now occurring regularly in Avoyelles Parish and Desha County due to warming temperatures. The necessary cumulative degree days (~2090, from the DD50 model) are now occurring regularly in Avoyelles Parish. The other locations, specifically Mississippi and Cape Girardeau Counties, are also showing temporal increases in season length and temperature, but have not yet reached these ratooning metrics. Overall, the temperature trends observed here, from south to north, are consistent with IPCC assessments (Hansen et al., 2006) showing that increases in global warming are not uniform, and enhanced land-surface temperatures (relative to the global average) are more probable with poleward and altitudinal increases.

Given recent trends, it is of interest to evaluate if projected temperature increases will be sufficient to allow ratooning to occur along

Table 6
Mean maximum and minimum daily air temperatures and the number of days during the frost-free season for historical and predicted climate years in which maximum air temperature exceeded 35 °C (95 °F) or minimum air temperature exceeded 24 °C (75 °F). Values are predicted from linear regression for historical (1976–2016), RCP4.5 (2030–2095), or RCP8.5 (2030–2095) scenarios with P-values indicated.

Location	Scenario	Year	Tmax °C	Tmin	Tmax > 35 °C Number of days	Tmin > 24 °C
Cameron Parish	Historical	1976	25	17	0	52
		2016	27	17	20	52
		P value	0.14	0.91	< **0.01**	0.97
	RCP4.5	2030	27	18	37	83
		2095	28	19	59	114
		P value	< **0.01**	< **0.05**	< **0.01**	< **0.05**
	RCP8.5	2030	27	18	32	83
		2095	30	21	108	154
		P value	< **0.01**	< **0.01**	< **0.01**	< **0.01**
Avoyelles Parish	Historical	1976	28	17	17	5
		2016	28	17	20	20
		P value	0.97	0.50	0.68	< 0.01
	RCP4.5	2030	29	17	60	46
		2095	30	17	91	76
		P value	< **0.01**	< **0.05**	< **0.01**	< **0.05**
	RCP8.5	2030	29	17	60	47
		2095	32	19	142	129
		P value	< **0.05**	< **0.05**	< **0.01**	< **0.01**
Desha County	Historical	1976	29	16	21	0
		2016	28	17	12	13
		P value	0.08	0.09	0.22	< **0.001**
	RCP4.5	2030	29	16	56	35
		2095	30	18	85	64
		P value	< **0.01**	< **0.05**	< **0.01**	< **0.05**
	RCP8.5	2030	29	17	57	36
		2095	32	18	134	117
		P value	< **0.01**	< **0.01**	< **0.01**	< **0.001**
Mississippi County	Historical	1976	28	15	15	0
		2016	29	17	18	27
		P value	0.26	< **0.001**	0.58	< **0.001**
	RCP4.5	2030	28	16	42	30
		2095	29	17	69	56
		P value	< **0.05**	< **0.05**	< **0.05**	< **0.05**
	RCP8.5	2030	28	20	44	28
		2095	32	23	124	109
		P value	< **0.01**	< **0.001**	< **0.01**	< **0.001**
Cape Girardeau County	Historical	1976	28	15	15	0
		2016	29	17	18	27
		P value	0.26	< 0.001	0.59	< 0.001
	RCP4.5	2030	28	16	42	30
		2095	29	17	69	56
		P value	< **0.05**	< **0.05**	< **0.05**	< **0.05**
	RCP8.5	2030	29	16	44	28
		2095	32	19	124	109
		P value	< **0.01**	< **0.001**	< **0.01**	< **0.001**

the northern part of the rice transect. These projections, using an average of six different global circulation models to estimate the impact of RCP 4.5 and 8.5 on cumulative degree days in the DD50 model, included how changes in temperature also impact other management aspects, such as planting, MC and RC times. The current results are consistent with recent temporal trends (since 1976); that is, they indicate that the thresholds needed for ratooning are likely to occur, even for moderate climate scenarios (e.g. RCP 4.5), well before the end of the century (RCP 4.5 for Cape Girardeau county being the exception) (see Figs. 6 and 7).

Overall, these data indicate that recent and projected trends in temperature could, potentially, allow ratooning to be practiced in many current locations where rice is grown, if not now, then in the current century. Given the ability of ratooning to increase production efficiency with minimal resource input, implementation of ratooning could represent an adaptive management strategy that would promote production resiliency with warming temperatures. However, it should be stressed that adaptation per se will also be dependent on concomitant changes in other management practices; for example, optimized use of cultivars that are appropriate for ratooning, optimal nitrogen application, pest management, etc.

While ratooning holds promise, it is also important to consider adverse consequences of rising temperature. As indicated in Table 6, there is increased frequency in either maximum or minimum daily temperatures exceeding 35 °C (95 °F) or 24 °C (75 °F), respectfully during the 1976–2016 period. Under either RCP4.5 or 8.5, these hot days/night frequencies will increase for all locations. Exposure to such warmer temperatures can be detrimental to rice production if they occur during major developmental stages such as anthesis or grain-filling (e.g. Baker, 2004; Coast et al., 2015). Alternatively, a longer growing season could provide for more adaptive management options in response to a warming climate by providing more flexibility with respect to selecting ideal planting dates to minimize heat stress impacts. In addition, projected CO_2 levels could also increase carbohydrate concentration in stems, and could accelerate regrowth following ratooning (Baker, 2004). Clarification on these issues is of obvious consequence for future implementation of any management strategy, including ratooning.

Finally, there is the question of global ubiquity of ratooning as an adaptive strategy regarding climate change and rising temperatures in rice systems. Ratooning is currently practiced in many countries including China, India, Japan, Swaziland, Philippines, Puerto Rico, Brazil, Thailand, and the U.S., but only in limited areas (Santos et al., 2003; Negalur et al., 2017). Yield is a primary driver for management, and particularly for tropical areas, double cropping rice can yield more than ratooning on an annual basis (Santos et al., 2003). In addition, ratooning implementation will be dependent on other economic and resource limitations, particularly water and labor availability, as well as rice system, i.e. upland or lowland rice. Overall, while there is considerable potential for ratooning (Krishnamurthy, 1988), its utility and adaptation will be contingent on region and current management; and may depend, in part, on projected increases in temperature on a country by country basis.

For example, in a summary of experimental work related to ratooning potential in India, Portugal, and the U.S., Negalur et al. (2017) concluded that low temperatures during the late stages of the main crop were the primary factors limiting ratooning practice. Recent climate studies indicated that global mean temperatures are rising at a rate of about 0.02 °C $year^{-1}$ (Cassman et al., 2010) and simulated daily mean temperature increases of approximately 0.7–1.3 °C were estimated for the major rice growing countries in Africa, Asia, and South America by 2030, a similar trend to what was simulated in the present study for the U.S. rice growing regions. Thus, as illustrated in the present study, warming temperatures and associated longer growing season duration because of a changing climate will likely present additional opportunities in major rice growing regions outside of the U.S… Modeling studies by Matthews et al. (1997), Masutomi et al. (2009), Espe et al. (2016), Li et al. (2017) and others have evaluated such purported impacts on changes in main crop rice yield in Asia, the U.S., and the Indochina peninsula. However, we are not aware of other modeling studies that have evaluated the potential of a second ratoon crop as a management adaptation strategy to take advantage of these changing temperatures.

Overall, management responses to climate change; e.g., shifting of planting dates, can have appeal as options that are easy (and inexpensive) to implement, relative to adaptations that require substantial infrastructure investments, e.g. irrigation (Lobell et al., 2008).

While the current study is specific to the U.S., it suggests that there may be other, substantive management options, that offer an efficacious means to adapt to climatic change. Ratooning management for rice systems may be deserving of additional evaluation in that regard.

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